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No upward shift of alpine grassland distribution on the Qinghai-Tibetan Plateau despite rapid climate warming from 2000 to 2014

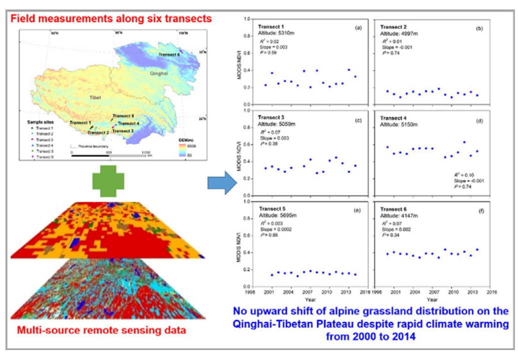
Ni Huang [a,*], Jin-Sheng He [b,c], Litong Chen [b], Li Wang [a]

[a] The State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China
[b] Key Laboratory of Adaptation and Evolution of Plateau Biota, Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining, Qinghai, China
[c] Department of Ecology, College of Urban and Environmental Sciences, Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing, China

HIGHLIGHTS

- The upper limits of grassland distribution were surveyed by field measurements.
- Remotely sensed data was used to analyze the change trends of alpine grassland AGB.
- No upward shift of alpine grassland distribution was found from 2000 to 2014.

GRAPHICAL ABSTRACT



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ABSTRACT

The distributions of many species show climate-driven shifts towards higher elevations, but evidence for elevational shifts is scarce for the alpine grasslands on the Qinghai-Tibetan Plateau. The upward shift of alpine grassland distribution from 2000 to 2014 was assessed with field measurements and satellite remote sensing data obtained across six elevational transects on the Qinghai-Tibetan Plateau. The aboveground biomass (AGB) of alpine grasslands varied with altitude and its data produced a bell-shaped curve. This was mainly due to the elevational dependency of climate change at the surface (i.e., producing drier climate at low elevations and wetter climate at middle elevations). The normalized difference vegetation index (NDVI) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) exhibited a positive exponential relationship with the AGB of alpine grasslands. Overall, MODIS NDVI initially increased, then peaked at median altitude sites, then decreased with altitude on each elevational transect. MODIS NDVI at the upper limit of alpine grassland distribution did not show a significant increasing trend from 2000 to 2014, even though land surface temperature increased and precipitation remained approximately constant. High spatial resolution Landsat data supported this result. Further analyses of MODIS NDVI at all other sites found no general increase in AGB towards higher elevations. The results suggest that the distribution of alpine grasslands on the Qinghai-Tibetan Plateau did not show an upward shift despite rapid climate warming having occurred from 2000 to 2014.

1. Introduction

The global average temperature has increased by approximately 0.74 °C over the past hundred years (from 1906 to 2005; IPCC, 2008),

* Corresponding author.
E-mail address: huangni@radi.ac.cn (N. Huang).

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and the period from 2000 to 2009 was the warmest since the introduction of instrumental measurements (Zhao and Running, 2010). Furthermore, this warming trend is assumed to be stronger at high elevations (Giorgi et al., 1997; Beniston et al., 1997; Pepin and Lundquist, 2008), such as those of the Qinghai-Tibetan Plateau. The Qinghai-Tibetan Plateau is the world's highest and largest plateau and has, on average, experienced greater warming than the Northern Hemisphere (Tao et al., 2014; Wu and Zhang, 2010; Wang et al., 2008). Moreover, the rate of annual temperature increase on the Qinghai-Tibetan Plateau has exceeded those of all other areas of the same latitude in recent decades (Zhang et al., 2014). The warming trend for the Qinghai-Tibetan Plateau is 0.40 ± 0.05 °C per decade ($p < 0.001$), and it has become much warmer since 1998 (Zhang et al., 2016).

Climate warming on the Qinghai-Tibetan Plateau has directly and rapidly affected the alpine grassland ecosystem (Guo and Lei, 2013; Yang et al., 2010) by reducing permafrost depth (Wang et al., 2012), decreasing soil water (Jin et al., 2009), and increasing soil temperature (Nan et al., 2005). Low temperature is considered one of the most important limiting factors for plant growth in alpine ecosystems; thus, temperature increase improve the photosynthetic capacities and growth rates of these plants (Li et al., 2011). On the basis of regional-scale remotely-sensed data analyses, a climate-driven greening trend in alpine grasslands has been well documented for the Qinghai-Tibetan Plateau (Xu and Liu, 2007; Yu et al., 2012; Tao et al., 2015; Du et al., 2016).

Compared to lowlands, mountains are characterized by steeper temperature gradients and fewer obstacles to plant migration. Thus, species can move across small distances within a given habitat to maintain their temperature range, allowing mountain plants to migrate rapidly when the climate changes (Bodin et al., 2013). Climate warming over the past century has prompted poleward and upward-elevational distribution shifts in many species (Savage and Vellend, 2014; Colwell et al., 2008; Chen et al., 2011). However, the magnitude and direction of such shifts vary tremendously among species and regions (Chen et al., 2011; Savage and Vellend, 2014; Pauli et al., 2007; Vittoz et al., 2008).

Alpine grasslands on the Qinghai-Tibetan Plateau show two types of vertical vegetation zonation (Fig. 1a, Types I and II). Without considering the impacts of climate warming, the biomass of alpine grasslands first rapidly increases (Type I) or exhibits no obvious change (Type II) as the altitude increases. The biomass of these two types peaks at median altitude sites. Then, the biomass of alpine grasslands decreases with altitude until reaching a minimum at the upper limit of the grassland distribution. We hypothesized that alpine grasslands at the upper limit of grassland distributions will show upward shifts during climate warming (Fig. 1a) because climate warming benefits vegetation growth at high altitudes (Yi et al., 2011b; Guo and Lei, 2013; Danby and Hik, 2007; Zhou et al., 2015). If remotely-sensed normalized difference vegetation index (NDVI) data can be used as a proxy for aboveground biomass (AGB) of alpine grasslands (Huang et al., 2013), a long-term NDVI dataset for alpine grasslands at high altitude sites should show a trend of increasing biomass concurrent with climate warming (Fig. 1b). However, field data obtained at the upper limits of grassland distribution, such as those of the alpine grasslands on the Qinghai-Tibetan Plateau, are almost entirely lacking. Without knowing the locations of the upper limits of alpine grassland distribution on the Qinghai-Tibetan Plateau, we cannot test the hypothesis that alpine grasslands have increased in altitude as the climate has warmed in the past decade. In this study, field experiments were conducted to investigate vegetation parameters and the upper limits of alpine grassland distribution on six elevational transects on the Qinghai-Tibetan Plateau. On the basis of the field measurements and remote sensing data, we tested the predicted ecological impacts of climate warming by analyzing the changes to alpine grasslands from 2000 to 2014. We aimed to answer the following two questions: 1) Can remote sensing data be used to monitor changes in alpine grasslands on different elevational transects? (2) Have alpine grassland distribution increased in altitude on the Qinghai-Tibetan Plateau from 2000 to 2014, based on the remote sensing analysis?

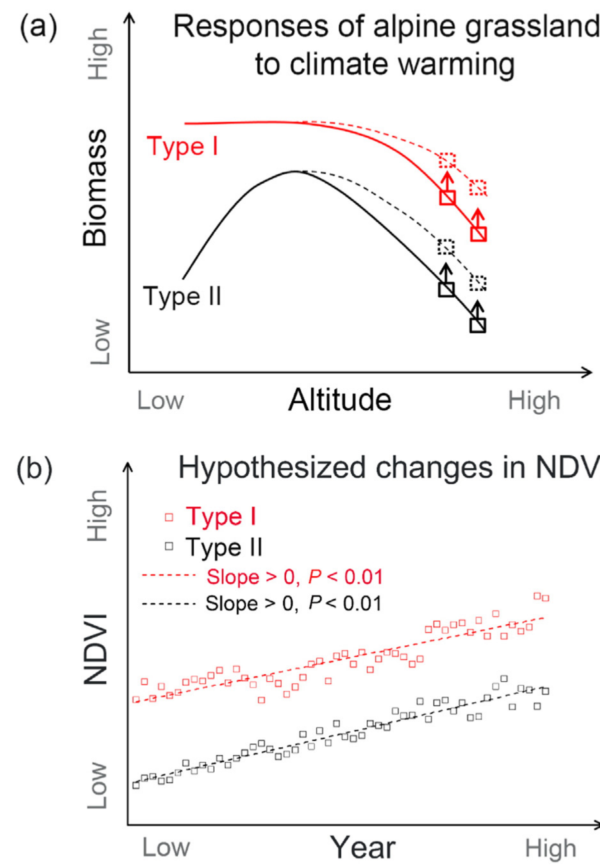

Fig. 1. (a) Schematic diagram describing the two types of vertical vegetation zonation of alpine grasslands (i.e., indicated by the solid line) and the responses of alpine grasslands to climate warming (i.e., indicated by the dashed line) on the Qinghai-Tibetan Plateau; (b) Schematic diagram describing hypothesized changes in normalized difference vegetation index (NDVI) at the upper limit of alpine grassland distribution on the Qinghai-Tibetan Plateau.

2. Material and methods

2.1. Study site

The study area was located on the Qinghai-Tibetan Plateau in Southwest China (78.3°–103.1° E, 26.5°–39.5° N). The Qinghai-Tibetan Plateau is the highest and largest plateau on earth, with a mean elevation of approximately 4 km above sea level (Fig. 2). The plateau exerts powerful thermal influences on the Asian climate system (Kueh and Lin, 2010; Mao and Wu, 2007), and it is one of the most sensitive regions to global warming (Yao et al., 2013; Kutzbach and Ruddiman, 1993). More than 60% of the plateau is covered by natural alpine grasslands (alpine steppe and meadow; Li and Zhou, 1998). From east to west along the precipitation and temperature gradients, three types of grasslands occur (i.e., meadow, steppe, and desert steppe). Roughly 60%–90% of the annual precipitation falls between June and September (Xu et al., 2008). The annual mean temperature is below 0 °C in most areas, and the warmest and coldest months are July and January, respectively.

2.2. Field data collection

Field experiments were conducted on six elevational transects on the Qinghai-Tibetan Plateau. The design of the transects considered the vertical zonation of alpine grasslands, site accessibility, and the representation of elevational gradients. Each elevational transect

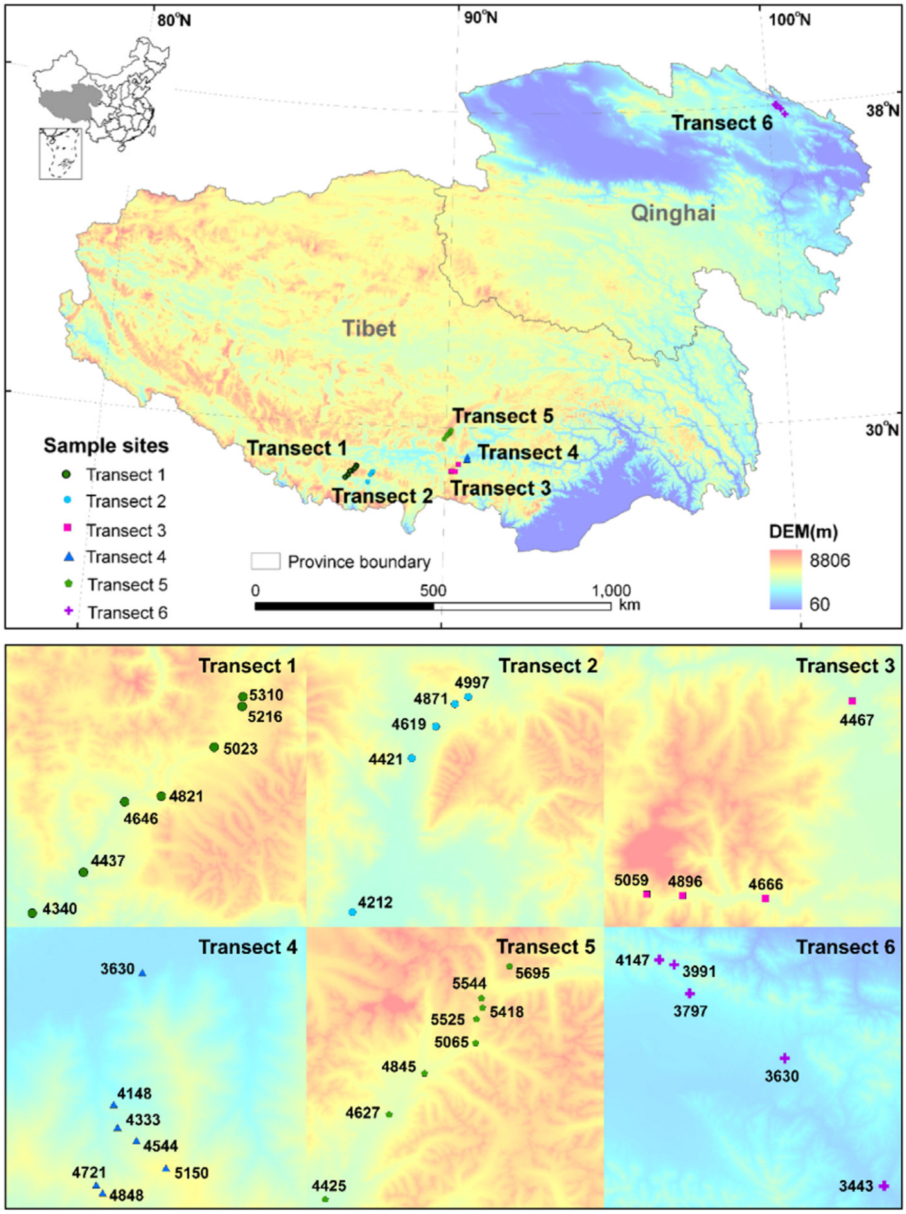

Fig. 2. Digital elevational map and the spatial distributions of six elevational transects on the Qinghai-Tibetan Plateau.

comprised 4–8 sample sites across the entire elevational gradient, and the sample site that had the highest elevation corresponded to the upper limit of grassland distribution (Fig. 2, Table S1 in the supporting information). Among the six elevational transects, Transect 6 was located in Qinghai Province, and the other five were located in Tibet (Fig. 2). Tibet has a greater proportion of higher elevation regions than Qinghai Province; thus, the sample sites of Transects 1 to 5 were at significantly higher altitudes than those of Transect 6 (Fig. 2, Table S1). Field experiments were conducted between July and August 2012. At each sample site, six plots (1 m × 1 m) were surveyed to measure AGB of alpine grasslands by the harvesting method. The average AGB of these plots was assumed to be statistically representative of the entire elevation zone. Data was also compiled on species characteristics to test whether vegetation changes with elevation had occurred as predicted at each elevational transect (Table S1).

2.3. Remote sensing data

The NDVI is the most widely-used satellite-derived metric for vegetation monitoring and ecological modeling. It provides a good measure of the greenness of vegetation (Guo and Lei, 2013) and has been used to estimate the AGB of alpine grasslands on the Qinghai-Tibetan Plateau (Huang et al., 2013). In this study, NDVI data were extracted from the Moderate Resolution Imaging Spectroradiometer (MODIS) 16-day composite vegetation index product (MOD13Q1), with a spatial resolution of 250 m, from 2000 to 2014 (https://ladsweb.nascom.nasa.gov/). We used MODIS NDVI data from the peak growing season of alpine grasslands, which was the period from mid-July to late August, and corresponded to three continuous 16-day periods. We extracted MODIS NDVI values for the locations of all sample sites for the following analysis. We selected NDVI values with good quality based on the VI quality and pixel reliability data layers. If one site possessed two to three good NDVI values, an averaged value was used to represent the site. If not, the only good value or the missing value was used.

To test the results obtained from the MODIS data, we used high spatial resolution (30 m) Landsat data. The Landsat Surface Reflectance product was obtained from the US Geological Survey's Earth Resources Observation and Science (http://earthexplorer.usgs.gov/). We used cloud-free images of the sampling sites obtained during the peak growing seasons of alpine grassland from 2000 to 2014. Based on reflectance

data for the near infrared (Nir) and visible red bands, the Landsat NDVI of the upper limit of alpine grassland distribution on each elevational transect was quantified by the following equation:

$$\boldsymbol{NDVI} = \frac{R_{Nir} - R_{Red}}{R_{Nir} + R_{Red}} \tag{1}$$

where R_x ($_x$ = Nir or Red) is the reflectance at the given wavelength (nm).

We did not have locally-observed climate data from locations close to each site with which to show the change trends in air temperature and precipitation along each elevational transect. Therefore, remotely sensed land surface temperature (LST) and precipitation were used as alternatives. For LST, we used the MODIS 8-day average 1 km daytime and nighttime LST product (MOD11A2), which has a deviation of ± 1 °C compared to ground measurements (Wan et al., 2004; Wan et al., 2002). For each 8-day period, if there was one good-quality daytime LST and corresponding nighttime LST, a mean LST was calculated by averaging them. For each year from 2000 to 2014, the mean LST was obtained by averaging the available good-quality mean LSTs of each 8-day period. If none of the 46 values were of good quality, we treated the year as missing. For precipitation, we used the TRMM (Tropical Rainfall Measuring Mission) 3B43 gridded precipitation product with a monthly temporal resolution and $0.25° \times 0.25°$ spatial resolution. This product combines precipitation estimates from multiple satellites and control rain gauges (Huffman et al., 2007). By quantitatively comparing with the precipitation estimated by the rain gauges and the satellite monthly averages, TRMM products have demonstrated reasonable performance on a monthly basis (Karaseva et al., 2012; Ballari et al., 2016). Annual precipitation from 2000 to 2014 was calculated by summing the monthly TRMM 3B43 values. The pixels from the mean LST and annual precipitation dataset that were centered on the sample sites were selected for further analysis.

2.4. Statistical analyses

To demonstrate the representativeness of MODIS NDVI for the AGB of alpine grasslands, we analyzed the relationship between field-measured AGB and corresponding MODIS NDVI values using nonlinear regression. Averaged MODIS NDVI values from 2000 to 2014 at each sampling site were also used to analyze the trend of MODIS NDVI with altitude at each elevational transect. This analysis tested the MODIS NDVI data quality from the perspective of capturing the vertical zonation of alpine grasslands.

Given that the ecological consequences of climate warming may be most pronounced at high elevations (Bertrand et al., 2011), the greatest temporal change in alpine grasslands was expected at the highest-elevation sample sites of each elevational transect. To test for a significant upward shift in alpine grasslands over time, we analyzed temporal trends in MODIS NDVI data at the highest sample sites using linear regression, where MODIS NDVI was the dependent variable and year (2000–2014) was the independent variable. Trends in MODIS NDVI were defined as the slopes of the linear regression. A positive slope indicates an increasing trend, and a negative slope indicates a decreasing trend. A t-test was used to estimate the significance of the trend. To verify the results acquired using MODIS NDVI data, the same analyses were conducted using available Landsat NDVI data because of its higher spatial resolution. In addition, we analyzed the temporal trend of remotely-sensed mean LST and precipitation from 2000 to 2014 using the same method. To further enhance the above analysis, MODIS NDVI trends at the sample sites across a whole transect, except the highest one, were analyzed to determine whether there was a shift of the peak AGB towards higher elevations. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS, Chicago, Illinois, USA).

3. Results

3.1. Trends of alpine grassland AGB and MODIS NDVI with altitude

Overall, the AGB of alpine grasslands along each elevational transect produced a bell-shaped curve (Fig. 3). Initially, AGB increased with altitude, with the highest AGB occurring at median altitude sites. Then, AGB showed a clear decline with altitude, as expected (Fig. 3). Alpine grasslands at Transect 6 exhibited higher AGBs than those of other transects. On the basis of all measured data, a statistically significant positive exponential relationship was observed between MODIS NDVI and AGB data at all sample sites ($R^2 = 0.29$, $P < 0.05$; Fig. S1). The spatial difference between a MODIS NDVI pixel (250 m × 250 m) and an AGB quadrat (1 m × 1 m) may be a source of mismatching between the two types of data. Accordingly, we excluded four sampling sites with unusually high AGB values, which greatly improved the regression between AGB and MODIS NDVI (R^2 increased to 0.63, $P < 0.0001$; Fig. S1). Thus, using MODIS NDVI as a proxy for alpine grassland AGB is reasonable, and considered suitable for the following analysis.

Fig. S2 shows trends in MODIS NDVI data with altitude for alpine grasslands at sample sites along the six elevational transects. Alpine grasslands at Transect 6 exhibited a higher mean MODIS NDVI value (0.55) than those of the other transects, with the lowest value observed at Transect 2 (0.16, Fig. S2). MODIS NDVI vs altitude along each elevational transect produced a bell-shaped curve that was similar to that for AGB vs altitude (Fig. 3 and Fig. S2).

3.2. Temporal trends in alpine grasslands at the highest site on each transect

Fig. 4 shows the interannual trend of MODIS NDVI recorded during the peak growing season at the highest site at each transect from 2000 to 2014. Grassland vegetation at the highest sites showed different temporal patterns among the six elevational transects. Except for Transects 2 and 4, the MODIS NDVI trends were positive at the highest sites from 2000 to 2014; however, all trends were statistically insignificant. Thus, along the six elevational transects, alpine grasslands at the highest sites were not affected by climate warming, as they did not increase significantly between 2000 and 2014 (linear regression, $P > 0.05$, Fig. 4) as we assumed they would (Fig. 1b). Additionally, higher spatial resolution Landsat NDVI data for the highest sites on Transects 1, 2, and 6 did not show statistically significant linear increases or decreases from 2000 to 2014 (Fig. S3). Therefore, although remotely sensed LST had an increasing trend at the highest sites on each transect (Fig. S4), and precipitation did not change obviously (Fig. S5), no upward shift of alpine

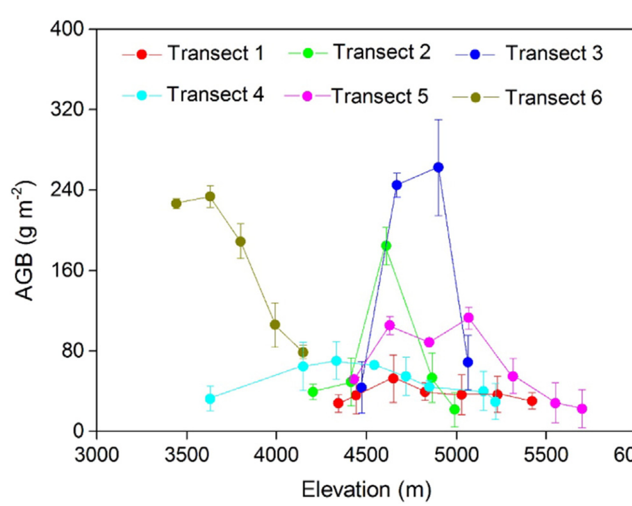

Fig. 3. Change trends of the aboveground biomass (AGB) of alpine grasslands at the sample sites with elevation along six elevational transects.

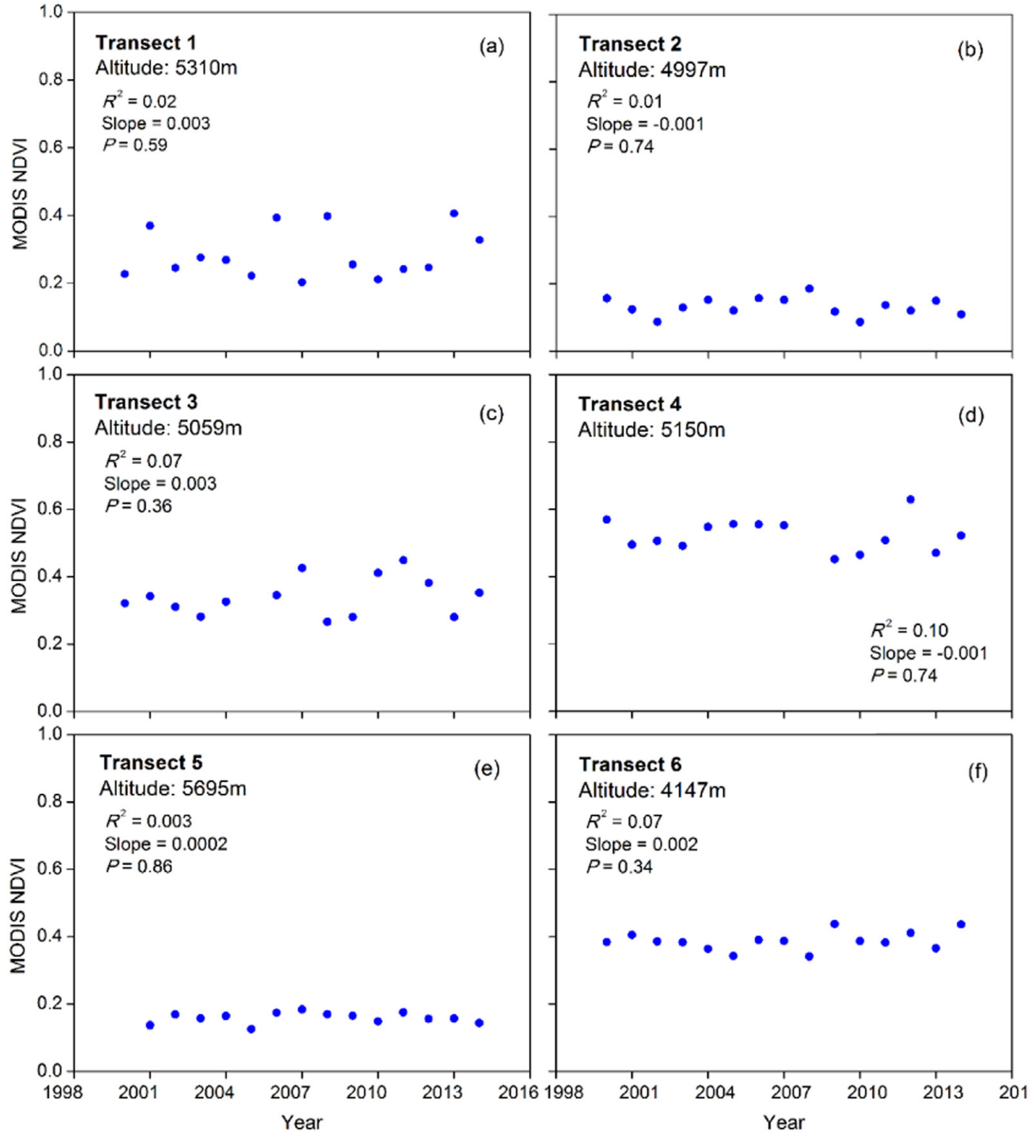

Fig. 4. Interannual change trends of the MODIS NDVI during the peak growing season of alpine grasslands at the highest site on each transect on the Qinghai-Tibetan Plateau from 2000 to 2014.

grassland distribution on the Qinghai-Tibetan Plateau was observed from 2000 to 2014 on the basis of remote sensing measurements.

Across the whole transect except for the highest site, MODIS NDVI only at the site with an altitude of 3991 m on Transect 6 showed a weakly significant increasing trend (linear regression, $P < 0.05$, Fig. S11d) from 2000 to 2014. MODIS NDVI at four sites on Transect 2 (altitude ranging from 4212 to 4871 m, Fig. S7) and one site on Transect 5 (altitude 4627 m, Fig. S10b) showed significant decreasing trends (linear regression, $P < 0.05$). Besides, MODIS NDVI at all the other sites of six transects did not show significant temporal trends (Fig. 4, Figs. S6, and S8–S11). Therefore, there was no general increase in AGB towards higher elevations along the total transects.

4. Discussion

4.1. Trends in alpine grassland MODIS NDVI with altitude

The alpine grassland vegetation types changed from alpine steppe to alpine meadow with altitude along each elevational transect (Table S1). This phenomenon is consistent with the distributional characteristics of climate and permafrost zones on the Qinghai-Tibetan Plateau (Zhou et al., 2015; Yang et al., 2010). As an indicator of vegetation growth, AGB is one of the most important characteristics of alpine grasslands. The bell-shaped curve of alpine grassland AGB vs altitude along each elevational transect is mainly due to the elevational dependency of surface climate change (i.e., drier climate at low elevations and wetter climate at middle elevations; Giorgi et al., 2010). This study demonstrates that MODIS NDVI can effectively estimate AGB variation (Fig. S1), which is consistent with previous studies indicating that NDVI is positively correlated with alpine grassland AGB (Chen et al., 2009; Huang et al., 2013). The similar bell-shaped curve of MODIS NDVI vs altitude along the six elevational transects agrees with our assumptions (Fig. 1a). These results demonstrate the feasibility of using data derived from MODIS NDVI for capturing the vertical zonation of alpine grasslands. A bell-shaped curve for forest species along an elevational gradient was also found by Bodin et al. (2013) in Southeast France. The highest MODIS NDVI values occurred mainly at the median-altitude sites of each transect, which may be because suitable temperature and water conditions occur at these altitudes (Yi et al., 2011; Zhou et al., 2015). At the lower altitudes of each transect, water may be a limiting factor for vegetation growth, and drought-tolerant species may be found (i.e., *Astragalus przewalskii* and *Artemisia younghusbandii*; Table S1).

With further increases in altitude, temperature begins to limit vegetation growth, and *Kobresia pygmaea*, which is suitable for high altitudes and cold environments, becomes the main vegetation type (Table S1).

The MODIS NDVI data varied with altitude along each transect. This phenomenon may be because the primary climatic factors causing grassland vegetation variation were different among the six transects (Tao et al., 2015). Among the six elevational transects, Transect 6 was located in Qinghai Province, and the other five were located in Tibet. Different terrain and topographical features cause climate differences between the two provinces (Chen et al., 2012; Wang and Guo, 2012; Yang et al., 2014), resulting in different grassland vegetation zones. Growing season precipitation was greater in Qinghai Province than in Tibet from 1982 to 2011 (Tao et al., 2015) because it has a longer rainy season caused by the East Asian monsoon rather than the South Asian monsoon (Molnar et al., 2010). Accordingly, denser grassland occurs in Qinghai Province than in Tibet. Transect 6 was located in the Qilian Mountains of northeast Qinghai Province, where the climate is semi-humid or humid and is suitable for grassland growth (Guo and Lei, 2013). Alpine grasslands on Transect 2 were distributed on the Transhimalaya mountain range of South Tibet, where the climate is semi-arid (Zhang et al., 2014). Thus, we observed the lowest MODIS NDVI values on Transect 2 (Fig. S2).

4.2. Temporal trends in alpine grassland at the highest site on each transect

Except for Transects 2 and 4, trends in the MODIS NDVI from 2000 to 2014 were positive at the highest sites of all elevational transects (Fig. 4). Further analysis at other sample sites (Figs. S6—S11) indicated that the MODIS NDVI at one site on Transect 6 had a weakly significant increasing trend. These findings agree with Tao et al. (2015), who demonstrated that alpine grassland greenness improved under climate warming from 1982 to 2011, based on remote sensing data for the Qinghai-Tibetan Plateau. Among the six elevational transects, only Transect 6 was located in a semi-humid or humid climatic region (Guo and Lei, 2013), which may partly explain why it had the only positive slope of MODIS NDVI that has been observed from 2000 to 2014 (Fig. S11d).

Transects 1 to 5 were located in the semi-arid area of South Tibet (Fig. 1). The significant decreasing trends of MODIS NDVI on Transect 2 (Fig. S7) may be due to grassland degradation caused by climate warming. Previous studies have demonstrated that climate warming greatly increases evaporation and intensifies vegetation degradation on the Qinghai-Tibetan Plateau (Gao et al., 2009; Du et al., 2004; Piao et al., 2012). Guo and Lei (2013) also found that the negative influence of temperature on vegetation is stronger in the southern part of the plateau than in the northeastern part, especially in the South Tibetan semi-arid area (Guo and Lei, 2013). Therefore, the negative effects of climate warming on alpine grasslands can explain the negative trends of the MODIS NDVI at the highest sites on Transects 2 and 4 (Fig. 4) and all other sample sites (Figs. S6–S11).

4.3. No upward shift of alpine grassland distribution with altitude on the Qinghai-Tibetan Plateau from 2000 to 2014

According to data obtained at the highest sites of all transects (Fig. 4), no upward shift of alpine grassland distribution was observed, despite remotely sensed temperature increasing and precipitation remain approximately constant over the study period. Further analysis of trends in the MODIS NDVI at all other sites found no general increase in AGB towards higher elevations along the whole transects (Fig. 4 and Figs. S6–S11). These results are inconsistent with expectations related to climate warming on the Qinghai-Tibetan Plateau (Tao et al., 2015; Liu et al., 2009).

At least three causes can be used to explain the lack of a clear upward shift of alpine grassland distribution on the Qinghai-Tibetan Plateau. The first may be the presence of time lags in biotic responses to climate change (Savage and Vellend, 2014; Bertrand et al., 2011; Corlett and Westcott, 2013; Vellend et al., 2013). Certain factors may prevent or slow the adaptation of vegetation to climate warming at high elevation sites. For example, unfavorable non-climatic conditions (e.g., soil pH or biotic interactions) can prevent germination or recruitment at higher elevations, even if the climate is suitable (Walther, 2003; Lafleur et al., 2010; Corlett and Westcott, 2013). Additionally, the amount of total soil- and plant-available C, N, and P decrease significantly with altitude because of decreasing temperature (Huber et al., 2007; Zhao et al., 2014). Bodin et al. (2013) attributed lag in species' distributional shifts in response to climate warming to a combination of low dispersal capacity (Svenning and Skov, 2004) and a tendency to acclimate rather than migrate (Hirzel and Le Lay, 2008). Wang et al. (2016) also found that global warming did not induce an upward shift of alpine tree-line ecotones, but promoted tree-line encroachment and densification in the southeastern Qinghai-Tibetan Plateau.

The second cause may be related to the typical characteristics of alpine plants. Tibetan grasses are largely perennial and propagate vegetatively; thus, the speed at which they can extend their habitat through migration is very slow, and reaching a new equilibrium between climate and vegetation may take many years (Yu et al., 2012). In addition, reports of climate warming are usually based on changes in atmospheric temperature measured 2 m above ground (standard meteorological data). However, in alpine landscapes, the low-stature vegetation is highly decoupled from atmospheric conditions due to micro-topography and snow deposition (Körner, 2003; Scherrer and Körner, 2010, 2011). Therefore, atmospheric warming might only have indirect and limited impacts on alpine grasslands, which might be part of the reason for the lack of a clear upward shift of alpine grasslands in this study.

The third cause may be due to the “effect size” of climate warming on alpine grasslands. Recent warming on the Qinghai-Tibetan Plateau has been about 0.4 °C per decade (Zhang et al., 2016). Without any specific knowledge of the air temperature difference mediated by elevation (adiabatic lapse rate) in the Himalaya, we assume this is equivalent to an altitude increase of about 70 m (at 0.6 °C per 100 m). Therefore, the AGB/NDVI observed at the upper limits of alpine grassland distribution should be maximal to the level of AGB/NDVI found in plots 70 m lower a decade earlier. As the elevational difference between the plots on each transect in the present study was >70 m (Table S1), it is difficult to quantify the difference exactly. We assume that AGB/NDVI will increase linearly with decreasing elevation from the upper limits. Hence, we calculated the expected increase in MODIS NDVI over a decade at a point 70 m lower than the highest site (Table S2). At the highest elevational sites on Transects 2 to 4 (Table S2), the expected increase in MODIS NDVI over a decade was smaller than the interannual variation (represented by the standard deviation). Hence, the data obtained by this study may have inadequate power to detect a trend that is smaller than the interannual variation. Therefore, the lack of a significant upward shift of alpine grassland distribution may be (at least partly) a statistical problem rather than the absence of upward migration. Increasing the numbers of sample sites and transects would be necessary to overcome this issue.

5. Conclusions

Field experiments were conducted to investigate AGB, species information, and the upper limits of alpine grassland distribution at six transects on the Qinghai-Tibetan Plateau. On the basis of field surveys and remote sensing data, this study provided compelling evidence that alpine grassland distribution on the Qinghai-Tibetan Plateau has not increased in altitude from 2000 to 2014, during which time the temperature has increased. Across all transects, there was no general increase in AGB towards higher elevations. However, limited sets of elevational transects, such as those of the present study, are especially prone to bias if they are not representative of the entire range of the

species of interest. We attributed the lack of a clear upward shift of alpine grassland distribution on the Qinghai-Tibetan Plateau to three causes: 1) potential time lags in biotic responses to climate change, 2) the typical characteristics of alpine plants, and 3) the "effect size" of climate warming. Further evidence from long-term monitoring and experimental studies are needed to verify our results.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.01.034.

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